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OCEAN CLIMATE STUDIES IN THE ARCTIC SEASONAL ICE ZONE

N. Untersteiner
University of Washington
Seattle, USA

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1. Introduction

The case for regional ocean-climate studies in the seasonal ice zone has been made in various ways for almost two decades, beginning with the Soviet "NEI Project" of the early sixties, which provided the original impetus for "POLEX", later renamed GARP Polar Sub-Programme (WMO-ICSU, 1975; Treshnikov et al., 1979). A list of documents on that subject is given in the bibliography.

The purpose of the present summary is twofold: 1) to highlight the essential scientific problems, and 2) to report on the status of some major projects under way or being planned for the near future.

It must be stressed at the outset that this report covers regional oceanographic studies in the Arctic only. This does not reflect a judgement that the northern polar seas are more important in the global climate system than the southern ones. The relatively more advanced state of planning of arctic projects is the result of two circumstances: one is the relatively greater knowledge of arctic oceanography and climate, and the other is the proximity of the Arctic to a large proportion of the world's population and,

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in particular, the emergence of the Arctic as a region known to possess massive deposits of natural resources.

2. Essential problems

Progress in understanding the role of sea ice in climate is hampered not so much by a lack of physical concepts and mathematical procedures as by a lack of data for driving and checking models. The key questions may be summarized as follows.

2.1. What is the mass balance of sea ice in a given region?

This balance is described (e.g., Untersteiner, 1963) as the change in time of the volume of ice present in a given area in terms of ice advection and production:

$$\frac{\partial(\rho h)}{\partial t} = -\hat{u} \cdot \mathrm{grad}(\rho h) - \rho h \nabla \cdot \hat{u} + \frac{1}{q}Q \qquad (1)$$

where ρ and h denote density and thickness, $\hat{u}$ the velocity, q the heat of fusion, and Q that part of the heat balance available for freezing or melting ice. Currently available data are insufficient to evaluate this simple statement of continuity. The terms containing (ρh) require observations of the ice thickness distribution in surface elements of suitable dimensions. The only tupes of data useful to evaluate these terms are upward-looking sonar profiles taken by submarines (e.g., Wadhams, 1981) and remote sensing data from aircraft and satellites. The few existing data sets of that kind are isolated in time and no numbers for (ρh) as a function of time have ever been derived. Observations of $\hat{u}$ are being taken since Global Weather Experiment 1979 (Untersteiner and Thorndike, 1982). Between 10 and 20 air-dropped data buoys measuring position and surface pressure have been in operation in the Arctic Basin since early 1979 and are yielding the first synoptic time series of surface stress and ice velocity over most of the central Arctic (Figure 1). These data will be valuable to drive and test certain types of ice dynamics models, but according to Thorndike (1982) it is not clear that these observations resolve the velocity field in sufficient detail to allow estimates of the term involving $\nabla \cdot \hat{u}$ in eq. (1).

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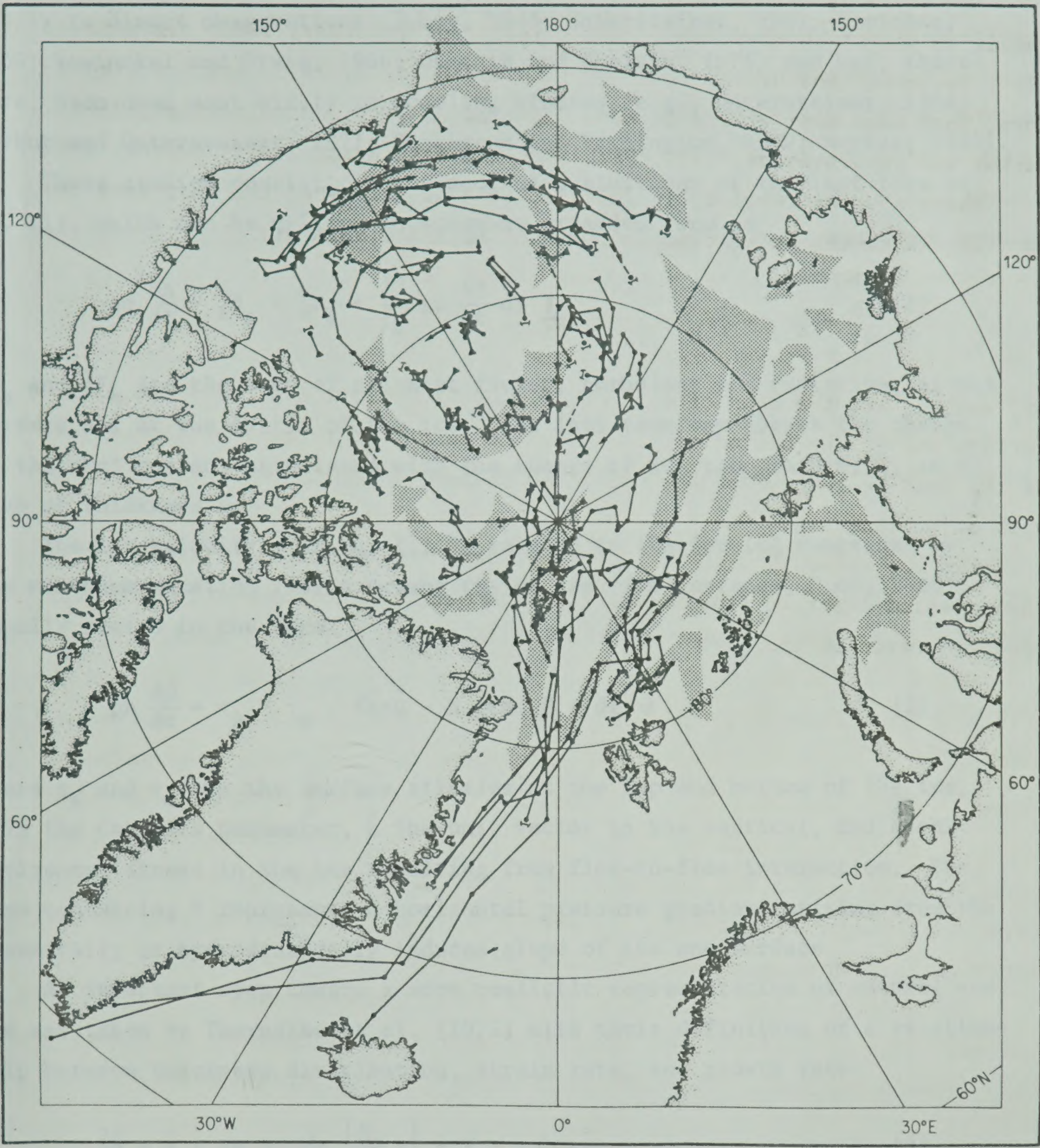

Figure 1. Drift paths of 45 air-dropped data buoys between January 1979 and December 1981. The buoys are positioned by ARGOS several times per day to an accuracy better than 1 km. They contain quartz-oscillator pressure sensors whose readings are accurate to ±1 mb, with a drift of less than 0.2 mb per year (adapted from Untersteiner and Thorndike, 1982). The stippled arrows indicate an early (Gordienko, 1958) estimate of the mean circulation of the upper several hundred meters of water in the Arctic Basin.

The thermodynamic term Q (ice sources and sinks) lends itself most easily to direct observations (Zubov, 1943; Untersteiner, 1961; Fletcher, 1965; Vowinckel and Orvig, 1966; Doronin and Kheisin, 1975) and has, therefore, been used most widely in modeling studies (e.g., Untersteiner, 1964; Maykut and Untersteiner, 1971; Parkinson and Washington, 1979; Maykut, 1982).

These studies consist, in essence, of evaluations of the last term in eq. (1), which can be written in somewhat expanded form as

$$\rho q \frac{dh}{dt} = \sum F_s + \sum F_b + \int_0^h \rho c \frac{\partial T}{\partial t} dz \qquad (2)$$

$\sum F_s$ and $\sum F_b$ are the sums of all heat fluxes, turbulent and radiative, at the surface and at the bottom of the ice. The last term represents the change of the heat content associated with the change of ice temperature, T, in a slab of thickness h.

The ice velocity $\hat{u}$ in eq. (1) is related to its forcing functions by the momentum equation (for a recent review see, for instance, Coon, 1980), usually stated in the form

$$\rho h \frac{d\hat{u}}{dt} = \tau_a + \tau_w - f\hat{k}\times\hat{u} - h \text{ grad } P + \text{div}\,\sigma \qquad (3)$$

where τ_a and τ_w are the surface stresses at the top and bottom of the ice, f is the Coriolis parameter, $\hat{k}$ the unit vector in the vertical, and σ the horizontal stress in the ice resulting from floe-to-floe interaction. The term containing P represents a horizontal pressure gradient arising from the dynamically or hydrostatically induced slope of the sea surface.

An important step toward a more realistic representation of natural sea ice was taken by Thorndike et al. (1975) with their definition of a relationship between thickness distribution, strain rate, and growth rate:

$$\frac{\partial g}{\partial t} + \hat{u} \cdot \nabla g = -\frac{\partial}{\partial} \left(\frac{dh}{dt} g\right) + \Psi - g\,\text{div}\,\hat{u} \qquad (4)$$

Here g denotes the fractional area covered by ice of a certain range in thickness. The thermodynamic growth rate dh/dt, a function of ice thickness and time, is given by eq. (2). The function Ψ describes the mechanical redistribution of ice thickness associated with the strain rate.

Reviews of our ability to model sea ice were given by Rothrock (1975), Doronin and Kheisin (1975), Rothrock (1979), and Hibler (1980). An effort to give theoretical modeling of sea ice a more secure observational basis was the Arctic Ice Dynamics Joint Experiment (Untersteiner, 1979; Pritchard, ed., 1980). The purpose of that experiment was the acquisition of a data set enabling us to evaluate all terms in eq. (3) and especially the term representing internal stress that cannot be determined except as a residual in the balance of forces. All needed data were taken as planned during a one year period in 1975 and 1976 in the Beaufort Sea at three manned and about ten automatic stations. One, to some degree unexpected, result was the accuracy with which surface air stresses can be derived from the geostrophic wind (Paulson, 1980; Brown, 1981). It was shown by McPhee (1982) that the planetary boundary layer in the ocean conforms with Rossby similarity scaling. This implies that the drag force between ice and ocean is proportional to less than the square of the relative velocity between ice and ocean. Based on the extensive data set obtained by Hunkins (1982) it was also shown by McPhee (1980) that during summer the internal ice stress is negligibly small and the ice velocity field is the result of external forces only. Including the propagation of internal stress in the ice in a dynamically complete sea ice model requires the definition of a constitutive law (relating stress and ice strain rate). A number of such laws have been formulated and tested (recent examples are Hibler, 1979; Coon, 1980; Rothrock et al., 1980). A universally applicable and useful constitutive law for sea ice has not been found, nor is it likely to exist. Natural sea ice is a material of such complexity that the choice of how to parameterize its mechanics will have to depend on the purpose of the calculations. Predicting its behavior on small space and time scales (for instance while it interacts with solid, immovable obstacles) will require the most sophisticated formulations including ice thickness distribution and re-distribution by strain, elastic strain, plastic yield criteria, the energetics of pressure ridge formation, hydrostatically induced stresses, and various anisotropies. On the other end of the spectrum, the description of the ice as a simple isotropically viscous Newtonian fluid may suffice for the very long term climatological computations (Hibler, 1980).

There are two limitations of these calculations at present. One is that they do not lend themselves to studying feedback with the atmosphere

and ocean, and the other is that the data for checking model results are not adequate.

An answer to the question posed at the beginning of this section will come from an incorporation of progressively more physics into the large scale models and from testing model results against the growing volume of data. The acquisition and methods of processing of such data should, to the greatest extent possible, be guided by their usefulness in both dynamic and stochastic modeling.

The second key question concerns the marginal ice zone:

2.2. What physical processes control the extent of sea ice where it is unconfined by land?

The equatorward expansion of sea ice during autumn and winter occurs both by in situ freezing and by the advection of ice. In a schematic sense, the sources for that advected ice are the highest latitudes where freezing sets in first. In contrast, the retreat of the ice boundary during summer occurs mainly by in situ melting. In the Arctic, that melting progresses all the way to the pole, reducing the ice cover to less than half of its maximum extent. From about 75 degrees northward, the ice thickness in most arctic sectors is great enough so that one summer's ablation cannot melt it. The surviving fraction is multi-year ice. In the Antarctic, there is a poleward land boundary for the sea ice at about 70 degrees. Therefore, virtually all antarctic ice melts each year, with the exception of a small region in the Weddell Sea.

It may be noted that the annual cycle of total sea ice cover in the Northern Hemisphere is asymmetric in the sense of showing a sharp minimum and a flat maximum. Comparison of the Arctic minimum extent with the Antarctic is not possible because it is near zero there, but the Antarctic ice maximum extent is also "flat" (or even more so than the Arctic one, Figure 2). A tempting speculative conclusion could be that, at the time of its maximum extent, the sea ice is approaching a quasi-equilibrium, and that a hypothetical persistence of winter conditions would not cause much further expansion of the ice cover. On the other hand, a hypothetical persistence of summer conditions in the Arctic would, of course, remove the ice cover entirely.

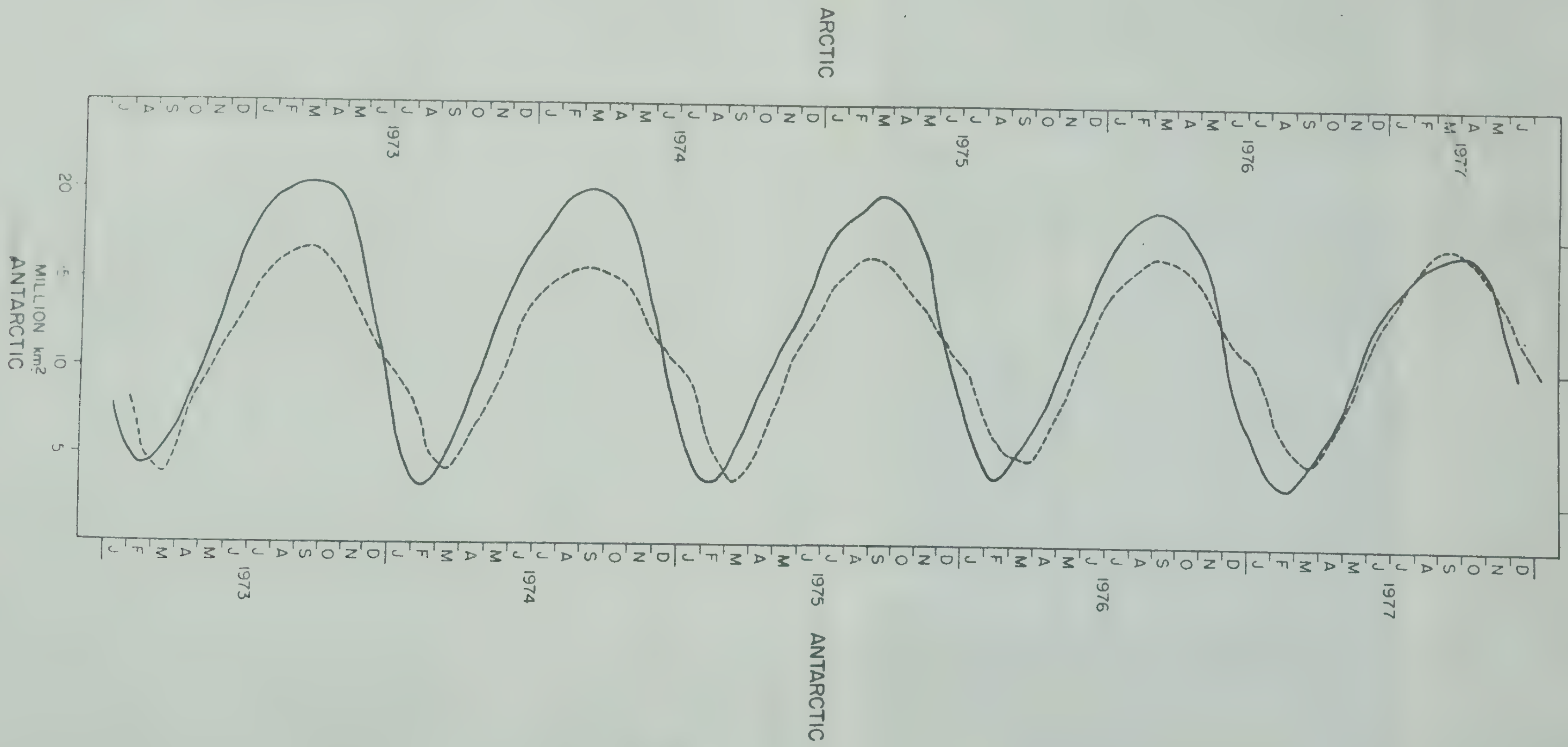

Figure 2. Total sea ice cover in the Arctic (Kukla, 1980) and Antarctic (Zwally et al., 1982). The definitions of "ice boundary" are consistent within each data set but differ between the two polar programs. (——— Antarctic, ------ Arctic)

The most basic question about effects controlling the position of the ice edge, i.e., separating advection from in situ freezing, has not been answered. Means of making the necessary observations are available and their use is being planned.

The most complex and almost entirely unanswered set of questions concerns the small and mesoscale phenomena at and near the ice edge. Cooling of the sea surface during autumn proceeds by mechanisms well studied and no different from those in other oceans. The onset of freezing introduces a sharp change in surface albedo, and a suppression of dynamic mixing in the ocean boundary layer simultaneously with an enhancement of convective mixing due to brine expulsion from the growing ice. The ice edge becomes a discontinuity, whose crossing induces modifications of both the atmospheric and oceanic boundary layers. The discontinuity itself is subject to horizontal displacement by air and water currents (including eddies) and its sharpness varies in place and time, depending on the combined effect of these currents in causing either divergence or convergence at the ice edge (Figure 3). Quasi-stationary features in the ocean, such as the East Greenland Sea Front, separating warm Atlantic water from cold arctic surface water and lying approximately over the Mohn Ridge (see Figure 4) raise the question

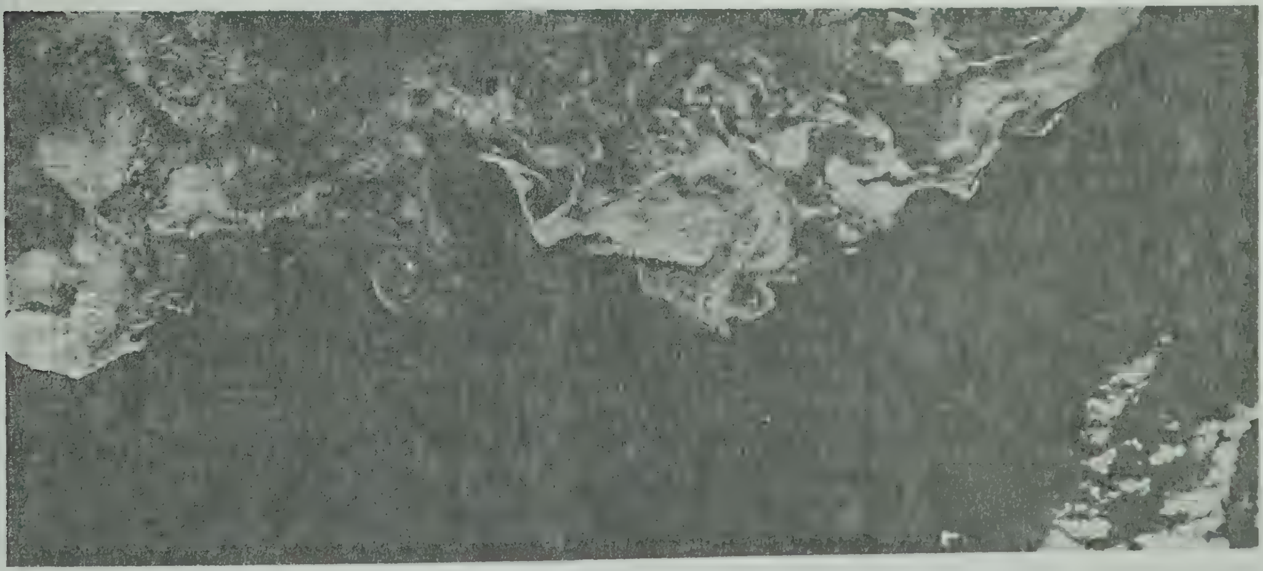

Figure 3. LandSat image of the sea ice boundary in the Chukchi Sea. Image length is 180 km. The eddies along the ice edge are believed to be caused by shear instability resulting from different surface roughness of the ice-covered and ice-free water.

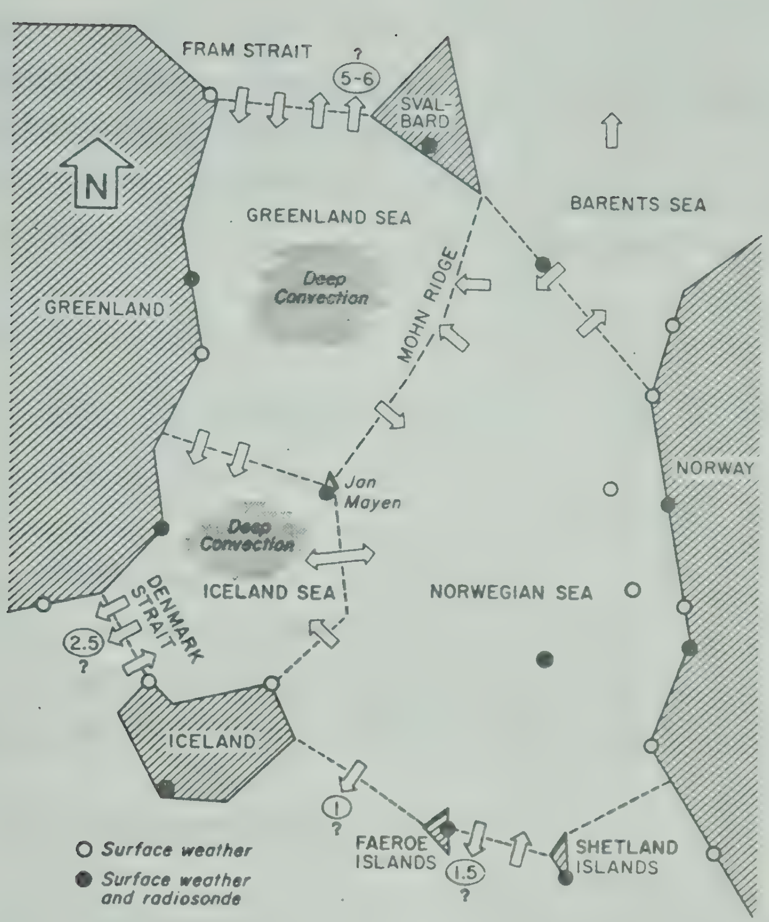

Figure 4. The Greenland - Norwegian - Iceland Seas "Cage". Numbers indicate tentative transport in Sverdrups. Full circles are surface and upper air weather stations. (Norway intends to augment the current network by 8 surface drifters per year, measuring surface weather and upper ocean parameters.)

whether they form an independent boundary for the eastward expansion of the ice, or whether they are to some degree caused or maintained by the regime associated with the presence of ice. And finally, there are surface waves whose attenuation in the marginal ice causes wave pressure on the ice floes as well as certain geometric floe patterns. These effects, along with a transition of air and water stress across the ice edge, lead to peculiar phenomena such as the heavily ridged outer ice edge in the Bering Sea (Bauer and Martin, 1980) or the formation of edge-parallel ice bands travelling ahead of the main edge during off-ice winds (Wadhams, 1982).

Some knowledge has been gained of these individual phenomena, but studies have been isolated in location and in time. In light of this, the question posed at the outset of this section might be amended to "How does one go about studying the physical processes in the marginal ice zone and their relative importance in determining the position of the ice edge?" The Marginal Ice Zone Experiment (MIZEX), summarized in section 3.1.2 below, is designed to answer these questions.

3. Regional studies being planned

3.1. Air-Sea-Ice Interaction Programs for the 1980's (ASI Program)

This program is being developed primarily as a contribution to the scientific objectives of the World Climate Research Programme (WCRP). It is based on recommendations made in the Scientific Plan for the WCRP (1981), on GARP Publication No. 16 on the physical basis of climate and climate modeling (WMO-ICSU, 1975), on GARP Publication No. 19 on the Polar Sub-Programme (WMO-ICSU, 1979), and on a number of additional planning documents listed in the bibliography.

A document describing the ASI Program (Untersteiner, ed., 1982) contains the following main elements:

- a statement of the problem
- a brief review of the prevalent and peculiar environmental characteristics of the marginal sea ice zone
- a description of the general research strategy, subdivided into the traditional categories of:
    - use of existing data
    - techniques and observing systems
    - monitoring studies
    - process studies
    - modeling studies

The ASI draft document was prepared by a number of interested scientists from the United States, Norway, and Canada.

3.1.1. The Greenland Sea Project

The Greenland Sea is a region favorable for a study of air-sea-ice interaction. It

- is a region where the most vigorous exchange of mass and energy occurs between an ice-covered and an ice-free ocean,
- is a region where seasonal and interannual variations of the ice extent are large and provide a strong signal for both observing and modeling,
- has the largest data base of any sub-region of the polar oceans because of historic records related to shipping,
- contains multi-year as well as first-year ice and therefore lends itself to the considerations outlined in section 2.1,
- contains ice that is bounded by a coast to the west, an unconfined ice boundary to the East, and two narrow passages to the north and south, which amounts to an optimal geometry for deploying observing systems,
- is a region of more or less unidirectional mean transports in the ice cover and in the ocean, enabling efficient use to be made of drifting observing devices,
- is surrounded by a relatively dense network of meteorological stations,
- is, by polar standards, highly accessible, from the permanent settlements along the Greenland coast, and by sea from Norway and the islands of Iceland, Svalbard, Shetland, and Faeroe.

A detailed plan for the Greenland Sea project is being studied at present. Major elements will be the ice balance (eq. 1) based on analyses of drifting buoy data and remote sensing images obtained from aircraft and satellites, attempting to keep track of the first-year/multi-year ice composition, air stress derived from surface pressure maps and the wind-driven component of ice motion, the role of the oceanic mixed layer in the heat balance of the bottom surface of the ice, and the role of the Greenland Sea oceanic front as it affects, or is affected by, the position of the ice edge. The latter observations will be related to the larger issue of deep convection in the Greenland Sea and the teleconnection of a polar ocean region with low latitudes by means of deep water masses emanating from the Norwegian Sea and traceable in the North and South Atlantic.

This project will be planned for at least five years and will therefore fall in the category of monitoring studies. It will also be seen as the

first step toward a more ambitious ocean monitoring study of the "cage" circumscribed by Fram Strait - Barents Sea shelf break - Norwegian coast - Shetland Islands - Faeroe Island - Iceland - Denmark Strait - East Greenland Coast (GINS Cage for Greenland - Iceland - Norwegian Seas Cage, Figure 4) as mentioned, for instance, in NAS-OSB (1982). A program of monitoring GINS Cage based on the rationale and methods elaborated by the international group on the North Atlantic Cage (CCCO, 1982) is not being proposed at this time, pending a thorough study of the existing ocean transport data across the several passages of the GINS cage, the further evolution of plans for the North Atlantic cage, and other feasibility assessments.

If the GINS Cage program does materialize, the Greenland Sea project will have made an important early contribution. If GINS Cage does not materialize, the Greenland Sea project can stand on its own rationale. Also, we believe that an intensification of observations in the Greenland Sea, no matter to what level, will yield a high return of useful scientific data, provided that they are obtained uninterruptedly for a succession of several years.

3.1.2. The Marginal Sea Ice Experiment (MIZEX)

MIZEX is a "process study" relating to the overall ASI Program (section 3.1) in a way qualitatively similar to the way GATE was related to FGGE. The objective of MIZEX is to answer the question posed in section 2.1, i.e., to elucidate the processes occurring in the marginal ice zone and particularly those that control the position of the ice edge.

In the Northern Hemisphere, the climatologically most important seasonal ice variations occur in the Greenland Sea, the Barents Sea, and the Bering Sea. In the latter two seas, ice formation is normally confined to the shallow waters of the continental shelves, while the ice of the Greenland Sea, even at its average minimum, extends over the deep waters of the Greenland Basin. Sea ice studies in the Barents Sea and Bering Sea, notably by Norway, the USSR, and the USA, have been underway for a number of years and shall not be described here.

A new multi-national project will be the Fram Strait MIZEX, which is currently being planned by scientists in Canada, Norway, the USA, Denmark, the United Kingdon, the Federal Republic of Germany, France, and Switzerland. Its experiment design is based on the definition of a "box" in which the

necessary parameters are to be measured. The base of the box is initially a square of about 200 km side length that will travel with the mean drift of the ice, beginning in a region north of Fram Strait and ending about 7 degrees farther south after a six-week period, sweeping out a strip shown in Figure 5. Observing platforms will be placed in an array straddling the ice edge. They comprise at least two open-water research vessels, two operating at the ice edge, one icebreaker drifting passively within the pack ice, and a number of automatic observing stations designed to observe their location, meteorological, ice, and oceanographic variables, including waves. In addition, it is planned to survey the area with airborne remote sensing instruments, and use all relevant satellite-borne remote sensing. The data

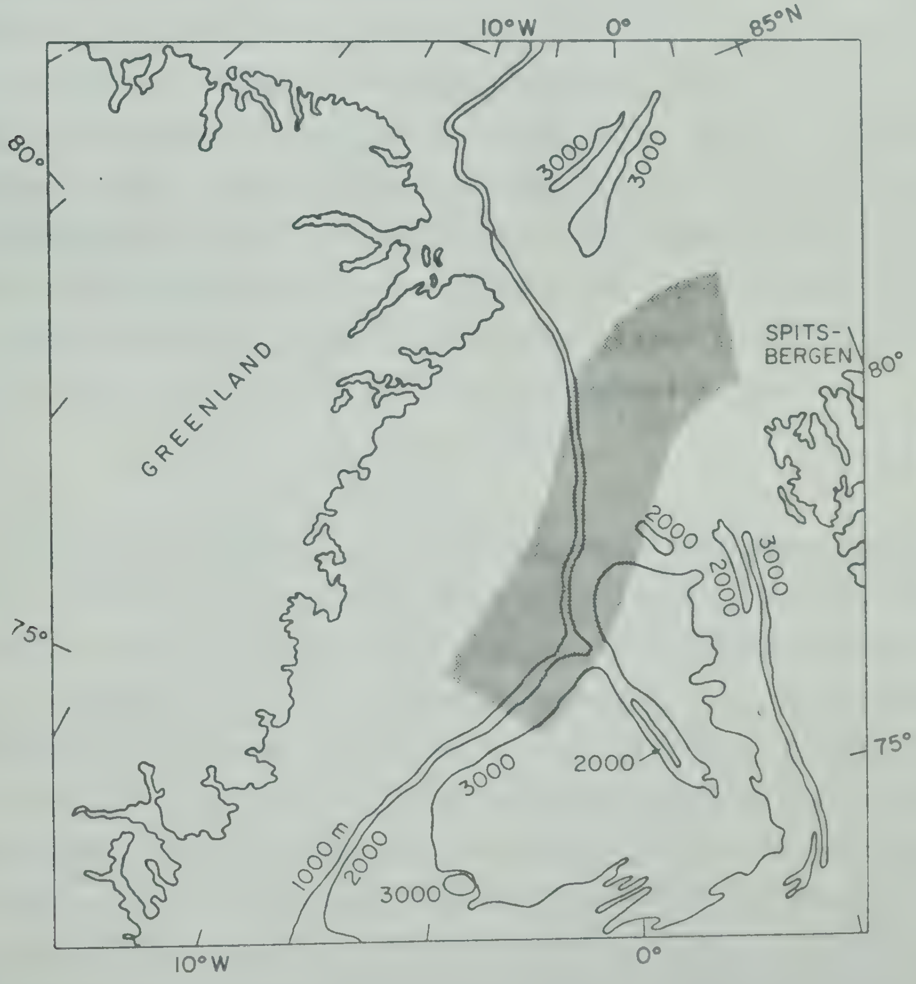

Figure 5. The stippled area is to be swept out by buoys, ships, and aircraft, taking various observations planned for the Marginal Ice Zone Experiment (MIZEX).

perhaps most needed and in shortest supply are profiles of the ice thickness. They can be obtained by upward-looking sonar attached to moored buoys, or by submarines. No significant use has been made to date of buoy-mounted sonars. A few isolated sets of data obtained by submarine have been published (e.g., Wadhams, 1981), but any systematic use of that highly efficient method of ice thickness data acquisition is largely beyond the influence of the civilian scientific community.

All technical means of making the observations needed for MIZEX are available today. As pointed out in section 4, a possible exception may be making the year-round distinction between first-year and multi-year ice. The extensive ground truth data to be obtained in MIZEX will be most useful in advancing our ability to interpret passive microwave imagery. In general, the part of MIZEX having to do with remote sensing will distinguish between remote sensing research for its own sake and the use of operational remote sensing methods in support of the overall objectives.

A preliminary scientific plan and experiment design for MIZEX (Johannessen et al., 1982) includes the conduct of a pilot study in summer 1983, intended primarily to establish an order of priority for the observations to be taken and the processes to be studied during the main phase of MIZEX. Plans for the latter include two full-scale field studies, one in summer 1984 and one at the end of winter 1986 or 1987.

NOTES:

- First drafts of the ASI and MIZEX documents were completed in July 1982. In the United States, these drafts will be reviewed by a panel of the Ocean Science Board, National Academy of Sciences, established especially for that purpose at the request of the US funding agencies. If, after due evaluations and revisions, these plans are approved, they will become guideline documents for use at the discretion of the US funding agencies in selecting proposals for the implementation of specific tasks contained in the scientific plans. The coordination of such efforts between researchers and research groups in different countries is expected to be accomplished on the basis of bilateral or multilateral agreements.
- The physical environment of the marginal and seasonal ice zone is home to a complex marine ecosystem containing some of the richest fishing grounds

and most prolific biomass production. For scientific reasons, as well as for reasons of cost sharing and efficiency, our plans for studying the physical environment should obviously be accompanied by plans to study the marine biology of the region. Every effort will be made to stimulate joint planning between physical and biological scientists toward mutually supportive joint enterprises.

3.1.3. The Fram Strait Monitoring Project

Monitoring the transport of water and ice through the Fram Strait has been widely recognized for many years as an observational need of high priority. Several older estimates of the ice export from the Central Arctic through Fram Strait have been summarized by Vowinckel (1964), who considers 3000 km^3 of ice per year, or 0.1 Sv, the most likely number. More recent analyses of LandSat images and drifting buoy data by Vinje (1977) seem to corroborate that approximate number. Current meter observations in the West Spitsbergen Current by Aagaard (1981) indicate a highly variable northward transport between 9 Sv and nearly zero in the course of one year (Figure 6). It is not known what relationships exist between such variations and the

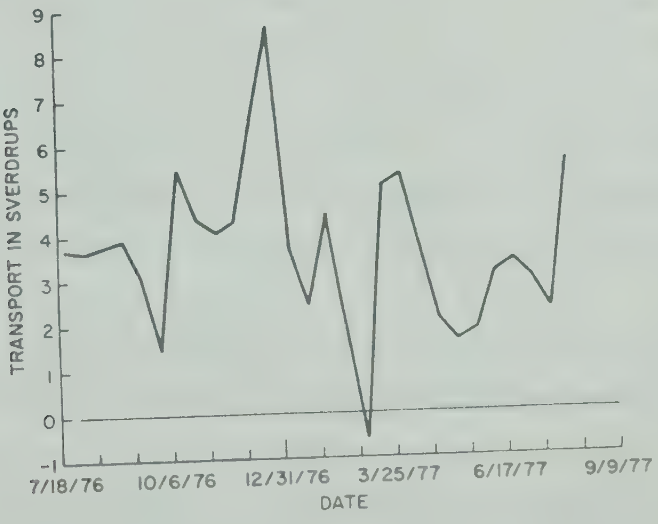

Figure 6. Transport by the West Spitzbergen Current according to moored current meter observations at 3 locations and depth of 100 to 400 m, according to Aagaard (1981).

return flow of the East Greenland Current, or other passages through the Canadian Archipelago or the Barents Sea. If a close correlation in space and time were found between the northward and southward currents in Fram Strait, the technical difficulties of monitoring ocean transport in the ice-covered East Greenland Current would be greatly alleviated.

The task of ocean monitoring across Fram Strait has recently been adopted by the Comité Arctique as one of their efforts toward arctic research. The Comité Arctique International (CAI) is a non-political, non-government, non-profit, international organization, established in the Principality of Monaco and housed within the Centre Scientifique de Monaco. The constitution of the CAI stresses research and dissemination of knowledge about all aspects of the Arctic, whether they are scientific, historical, economic, or sociological. Particular emphasis is placed on the promotion of rational, harmonious, and non-destructive development of arctic resources.

In 1981 the CAI commissioned SCOR Working Group 58 (On the Heat Balance of the Arctic Basin) to prepare a draft scientific plan for a multi-year project of monitoring oceanic transport through Fram Strait. This draft was prepared by SCOR WG 58 and additional invited experts in late 1981 and is presently undergoing refinements. CAI plans to request funding for the Fram Strait project from several oil companies. Presumably, the oil company interest is based on the transport of hydrocarbons by icebreaking tankers from North Canadian fields, and by the prospects of hydrocarbon deposits on the East Greenland shelf (which is, in part, the geological counterpart of the Norwegian Sea shelf). The practical usefulness of the Fram Strait data would be a knowledge of ice morphology and the possibility of developing some environmental predictive skill in support of the industrial activities anticipated to occur during coming decades.

Even though the motivation for CAI's Fram Strait project is different from that of the World Climate Research Program and similar enterprises, methods and products are broadly overlapping.

At this time, the monitoring planned by CAI is to be concentrated in the geographical region of the Fram Strait. Thus, the combination of that project and the Greenland Sea Project outlined in section 3.1.1, though differently motivated, makes a desirable and mutually supportive compact. The scientific community engaged in oceanographic and climate research should make every effort to assist the Comité Arctique planners in their

efforts, and both parties should seek to combine observing systems and data processing for dual use wherever possible.

A firm and detailed experimental design for the Fram Strait project cannot be given at this time, but it will be available in late 1982 in preparation for a proposed starting date in 1984.

4. Observing techniques

The rapid evolution of general purpose oceanographic instrumentation during the past decade has been summarized by Baker (1981). A few items of special relevance to the polar regions shall be mentioned here.

a) The air-droppable data buoy with ARGOS positioning and an atmospheric pressure sensor has been mentioned earlier (Figure 1). The Norwegian version of that buoy carries, in addition, an external temperature sensor. Efforts are under way in the US to design an improved version of that sensor for use with the next generation of air-dropped buoys. The next most important addition is a temperature and conductivity sensor chain reaching through the mixed layer (ca. 150 m). Water temperature sensing elements pose no problem. The problem of stability of conductivity sensors is well known and work is progressing at several institutions to eliminate it.

   Air-dropping buoys with sensor chains seems useful only in the marginal ice zone. Air deployment of such buoys in the interior pack ice in open or thinly covered polynyas is feasible but not advisable since polynyas have the highest chance of closing and destroying the buoy. For sophisticated buoys carrying sensor chains, it appears appropriate to return to the spar configuration and manual installation. The life expectancy of such buoys can be increased by installation in thick ice and by adding battery capacity. Operating in that mode opens the possibility of adding current meters and other sensors (vertical acceleration due to waves, ambient noise, radiation, etc.).

b) An addition to such buoys is a sonic device of the type described by Untersteiner (1966) to measure accretion or ablation at the underside of the ice. Along with an easily obtained temperature profile within the ice, the readings of such an instrument yield the vertical heat flux in

the water (McPhee and Untersteiner, 1982), a parameter virtually unobtainable routinely by flux measurements in the ocean boundary layer.

c) Observing oceanic transport parameters by means of moored current and temperature sensors, and surface tilt by pressure gauges mounted at the sea floor and other levels in the interior of the ocean have proven successful (Wearn and Baker, 1980). Deploying such devices in ice-covered waters is easy. Their retrieval is difficult but possible. The main issue here is to choose locations and numbers of instruments so that representative transports through a given cross-section can be calculated.

Monitoring the transport of ice is possible in a number of ways. Vinje (1977) used successive LandSat images to determine the horizontal velocity field of the ice in the northern Greenland Sea. This method is accurate, but requires assumptions for the ice thickness in order to yield numbers for the volume transport. Ice drift velocity measurements can also be obtained by observing the Doppler shift of the backscatter from shore-based radar (CODAR). This method has the same limitation as the use of sequential satellite pictures. Moored, narrow-beam, upward-looking sonar devices in combination with measurements of ice velocity can be used to monitor ice volume transport. Combining upward-looking sonar with side-looking sonar Doppler shift eliminates the need for independent observations of ice velocity. Devices for doing this are available and should be considered for future ice transport monitoring programs.

d) Owing to the large changes of radiative properties of the sea surface associated with freezing and thawing, remote sensing from aircraft and satellite is an obvious and widely used and studied technique. Applicable frequencies in the electromagnetic spectrum range from visible light to centimeter-waves. A comprehensive review of the use of remote sensing in sea ice research was recently prepared by NASA (1979) and Carsey and Zwally (1982). Only one problematic issue shall be mentioned here because it is intimately related to one of the central questions of the ASI program (see section 2.1). It was shown by W. Nordberg of NASA and his coworkers more than a decade ago (Wilheit et al., 1972; Gloersen et al., 1973) that, irrespective of the thermometric surface

temperature, first-year and multi-year sea ice show different apparent brightnesses in the centimeter wavelength range. The great value of being able to make that distinction was apparent. If we were able to map, at weekly or monthly intervals, the percent coverage by first-year and multi-year ice of the whole Arctic Ocean (or even a sub-region such as the Beaufort Sea or Greenland Sea) we would have the important control on a wide range of dynamic and thermodynamic calculations and an understanding of the overall mass balance and its seasonal cycles. Despite strenuous efforts to unravel the complex physics of microwave emissivity (dependence on brine volume, air content, solid salts, crystal fabric, snow cover, melt ponds, and surface roughness), the problem is proving to be obstinate. While considerable progress was achieved in mapping total ice extent in both hemispheres (e.g., Zwally and Gloersen, 1977) and, to a lesser degree, in mapping ice concentration near the ice edge, no credible data exist for the regional distribution of first-year/multi-year distributions and their evolution in time. In addition to the problems related to passive microwave physics, it is intrinsically difficult to obtain independent measures of the age of the ice in a given region. Low surface salinity is typical of ice that has survived one summer's melt, but at present there are no means of remotely measuring surface salinity. Ice thickness alone is a measure of age only at certain times of the year and in certain regions. And the "roundedness" of macroscopic surface features, also typical of ice subjected to several weeks of surface melting, does not lend itself easily to quantitative, regional measurements.

Studies of all the problems mentioned above are in progress (e.g., Johannessen, 1982). In view of the prospect that passive microwave images will be operationally available at least throughout the coming decade, every effort should be made to improve the techniques for routinely producing maps of ice concentration and multi-year and first-year ice (Carsey, 1982).

e) In the marginal ice zone, where little is known about density structure and dynamic topographies, conventional hydrocasts will undoubtedly retain their established value as a source for background data in support of more specialized studies. In the Central Arctic, however, one cannot

help but note the small return that standard hydrography has yielded during the past two decades. The baroclinic circulation in the Arctic Basin is extremely sluggish by comparison with other oceans. The picture of an anticyclonic gyre, centered somewhere in the Beaufort Sea, and a transpolar driftstream setting from the New Siberian Islands toward Fram Strait has received little refinement since they were described by Worthington (1953). Deep casts, typically made from long-term, manned drifting stations, are generally non-synoptic and their location is a matter of passive ice drift, rather than choice. Despite the thousands of casts taken since the International Geophysical Year 1957-58, efforts to model the mean circulation in the Arctic Basin are still compelled to use a mean dynamic topography of the ocean that is about 30 years old (see also Coachman and Aagaard, 1974).

f) Modern methods of using tracers are opening new vistas in that regard. They employ two basic approaches. The first is related to the injection of nuclear fission products into atmosphere and ocean which peaked in 1963 and ended at that time with the international test ban treaty. The fission products and their daughter elements are used to track concentrations in the ocean and deduce movement and residence times of water masses. The other, and overlapping, approach is to use naturally produced gaseous tracers (especially Helium 3) whose concentrations in the ocean and the atmosphere approach an equilibrium at the sea surface. Vertical motions in the ocean remove water masses from contact with the atmosphere. If the time of that contact is defined as water mass age zero, then the tracer concentration after removal of the water mass from the surface becomes (with certain corrections) a measure of the age of the water mass. With the rapidly developing accuracy of measuring tracer concentrations, additional useful tracers are being continually identified.

The use of such tracer methods, especially in a slowly circulating ocean, is potentially superior to the attempt to interpret traditional hydrographic data, since tracers indicate the cumulative effects of circulations over years and decades that are too subtle to be detected by hydrographic analyses. Only a few tracer studies in polar oceanography have been performed to date (e.g., Top et al., 1980; Östlund, 1982) and greatly increased use of these methods should be made in the future.

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